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Direct Current Measurement Based Steer-By-Wire Systems for Realistic Driving Feeling

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Abstract **- In this paper, a method to reproduce realistic driving feeling and improve the returnability of steer-by-wire systems (SBW) is proposed by measuring the roadwheel motor's current directly. The key contribution presented here is a novel method to recreate the driving feeling in term of force feedback with simple and cheap current sensors. A current sensor is used to fully measure the steering torque on the rack of steering mechanism. This measured steering torque therefore, includes the overall effects of road conditions, aligning moments, tire properties and so on. Beside that, a free control scheme is proposed to improve returnability as well as the handwheel stability in a free motion. Moreover, during this research, the significant frequency effect of handwheel motions was found. This effect could be useful and valuable for improving steer-by-wire development based on torque-map based method. This method is investigated with simulation results using the control design and simulation module in LabVIEW programming language. The simulated results show that this method offers a cheaper and simpler solution for the development of steer-by-wire systems. In addition, stability and returnability of handwheel in steer-by-wire systems could be improved.**

I. INTRODUCTION

Steer-by-wire is the innovative version of an automotive steering system shown in Fig. 1. In the SBW system, a driving signal given by a driver is transmitted to the road wheels through electrical wires while this signal is transmitted through mechanical and, or hydraulic linkages in conventional steering systems.

Thanks to the absence of the mechanical connection between the handwheel (HW) and the roadwheel (RW), SBW systems offer several advantages such as lager space in the cabin, freedom in car interior design, no oil leaking, and less injury in case of car accidents. However, there are also numbers of disadvantages due to the lack of mechanical connection. For example, the lack of realistic driving feelings, which is the driving feelings for the driver as in conventional steering systems. SBW systems can be out of order because of electrical faults. In addition, the difficulty of the free control of the handwheel, which is the HW behavior, after the driver's hands release at certain steered position of the HW. One of the most challenging issues on SBW development is how to give drivers the realistic feelings or realistic force feedback which is the same as conventional hydraulic steering systems. The force feedback for SBW systems has been studied by many researchers, [1], [2], [4], [5], [9]. In 1966, E.R Hoffmann [1] and P.N. Jouber studied on the effect of changes in some vehicle handling variables on driver steering performance.

In 1995, Andrew Liu and Stacey Chang [2] described three experiments conducted in a driving simulator that explore how force feedback information may be used by the driver and to see how steering torque information is affected by the variance of the steering movements. Recently, disturbance observer-based approach is implemented by Yih, P. and Gerdes, J.C. [13], and Shoji Asai, 2004 [5], etc. For this method, the realistic feelings could be obtained from the dynamic model using an observer. However, the exact models of steering system and vehicle as well as powerful microcontrollers are essential here.

Some papers [15], [16],have proposed a torque map-based method, in which, the force feedback can be obtained with a force control loop. A torque map is a reference input of the force feedback control. This torque map is the combination of several signals such as vehicle velocity, HW angle, etc. Attaching torque sensors to the rack of the steering system is proposed by PI [16]. However, prices and heavy working conditions of torque sensors in steering system are the biggest disadvantages for those methods.

In this paper, we propose a novel method to make the realistic feelings in the SBW system the same as the driving feelings in hydraulic power steering systems. This method is inexpensive, easy to develop, and less complexity.

II. STEER-BY-WIRE SYSTEM

A. *Conventional mechanically connected steering and SBW*

In conventional mechanically connected steering systems, such as hydraulic power assisted steering systems, Fig. 1a; the HW rotation given by a driver is transmitted via a intermediate shaft. The column is connected to the rack and roadwheels. Therefore, the roadwheel angle is proportional to the HW rotation. An amplified hydraulic pump is used to reduce the driver's steering efforts.

In SBW, Fig. 1b, the intermediate shaft, and the hydraulic pump are removed. And several position sensors and actuators are attached to the HW and RW. The encoder at HW is to observe HW motion. The HW motion, then converted into electrical signals and wired to an electronic control unit (ECU). The ECU controls an RW actuator for rotating the RW part in the same manner of the HW behaviors. The second encoder at

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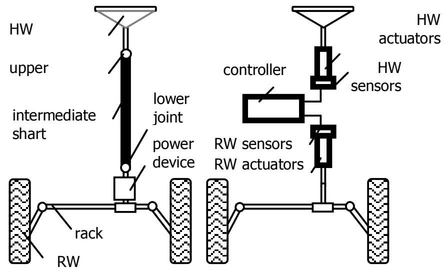
RW is for implementation of closed-loop position control. Because of the absence of physical connection, a DC motor at the HW is needed to recreate driving feelings.



(a) (b)

Fig. 1 Conversion from conventional steering system to SBW

To make SBW features close to conventional steering systems, several requirements have to be met. Position tracking, which is the fundamental function of a normal steering system. This ensures the RW exactly copy the HW motions for accurate steering control. Realistic force feedback, which makes steer-by-wire system to has the same driving feelings as in a hydraulic steering system. From previous researches [3], [5], [8], [10], the driving feeling is one of the most difficult issues for steer-by-wire development. Free control refers to the response of the HW after a sudden release from the certain position of the HW. In this case, a quick return to center with minimal overshoot is desired [6].

B. Modeling of Steer-By-Wire System

Basically, a SBW system can be considered as a two-port network whose schematic arrangement is shown in Fig. 2. The driver gives position to the HW. Then, this motion is tracked by the RW. In turn, the interaction of the road surface and tires produces an interacting torque. With mechanical dynamics, this torque causes the driving feeling for drivers.

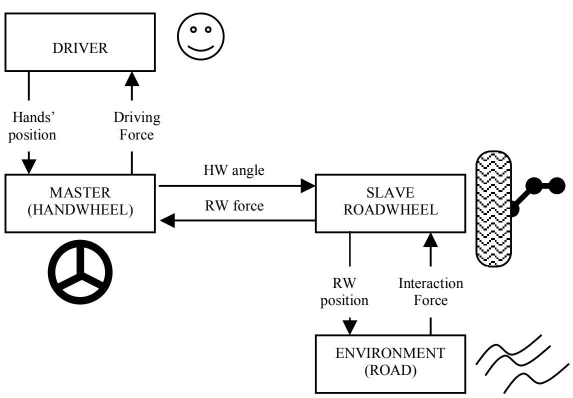


Fig. 2 SBW is considered as a two-port network

The model of SBW system simplified as the Fig. 2 consists of two parts, handwheel and roadwheel. In the HW part, θ_{hw} angle is the HW input given by the driver, τ_h is human torque applied on the HW. The equation for SBW modeling is presented in equation (1). τ_{RWact} is HW actuator torque, τ_{HWfr} is friction of the HW part. For other explanation of notations in this equation, please see [TABLE 1].

$$J_{hw}\ddot{\theta}_{hw}+b_{hw}\dot{\theta}_{hw}+\tau_{HWfr}=\tau_h+\tau_{HWact} \quad (1)$$

In the RW part, θ_{rw} is the RW actuator's angle. RW is actuated by motor torque τ_{RWact}. If there is a contact between tires and the road surface, aligning torque τ_a will occur because the existence of caster and kingpin angles in a steering mechanical structure. τ_{RWfr} is friction of the RW part. Finally, with tire-to-ground contact, the model of RW part of the SBW system can be expressed as equation (2).

$$J_r\ddot{\theta}_{rw}+b_r\dot{\theta}_{rw}+\tau_{RWfr}+\tau_a=\tau_{RWact} \quad (2)$$

The location of torques, angles, and moments are illustrated in Fig. 3.

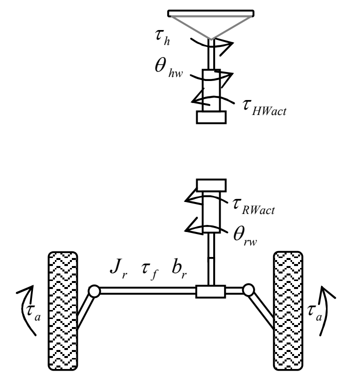


Fig. 3 Modeling of a SBW system

III. Current Approach

In this section, we focus on the force feedback implementation for the SBW systems. Normally, the force feedback known as driving feelings is from the RW part. This includes moment of inertia and damping; align moment, joints' friction. The feedback force is also affected by tire properties, road condition, vehicle velocity, and so on.

In hydraulic steering systems, this force is transmitted to a driver after power modification of based on a hydraulic pump for convenient of HW control. However, in SBW system, this force must be artificially recreated by the HW actuator. Therefore, a realistic force feedback including all the mentioned effects becomes an essential factor in SBW.

A. *Model-based approach*

Normally, to recreate the force feedback, the moment of inertia and damping, and friction can be calculated as soon as their constants are identified. The most complex and difficult issue is how to calculate align moment.

To solve this, several solutions are introduced. Those include model-based approach [8], [13], [18], torque sensor-based method [9], [15], torque-map method [3], [15].

Recently, J. Christian Gerdes and al, [13] have developed HW force feedback based on a disturbance observer in which the align moment is considered as a source of disturbance in the system dynamics. Therefore, the aligning torque can be estimated without any torque sensors. However, disturbance-based approach requires a powerful microcontroller for calculating the force feed back. And the estimated signal may be not exactly the same as the actual aligning moment.

B. Torque map-based method

Torque map method is a good way to avoid the calculation of aligning moment for solving force feedback issue. One of the torque maps is developed by Se-Wook Oh & et. al. Their main concept was the torque map is built based on two signals, vehicle velocity and HW position, Fig. 4. In particular, the relationships between the HW angle and vehicle velocity are defined as equation (3), and (4).

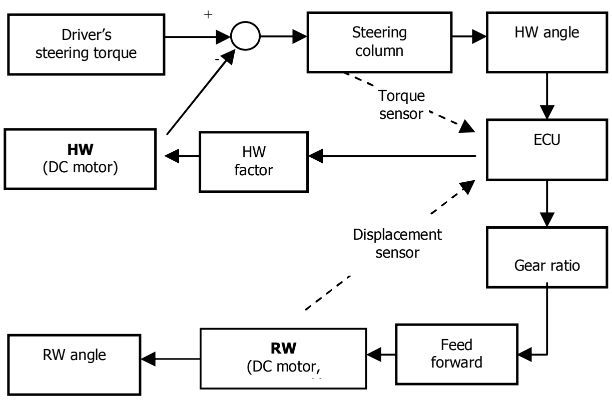


Fig. 4 Control scheme of the torque map method

Angle effect term:

$$y_{SW} = K_{\alpha}\sqrt{\theta_{hw}} \quad (3)$$

Velocity effect term:

$$y_V = -K_{\beta}x^2\left(\frac{1}{3}x - \frac{1}{2}V_{V\max}\right) + T_{in} \quad (4)$$

Where K_α, K_β are constants defined by developers. $V_{V\max}$ is the vehicle's maximum velocity. x is vehicle velocity. T_{in} is the initial torque. The summation of angle effect term y_{SW} and velocity effect term y_V is the total force feedback (or called as driving feeling) in this method. With the torque map, it is easy to recreate force feedback because the HW angle θ_{hw}, and the vehicle velocity V_V can be easily measured in any today vehicles. However, other factors such as rotating frequency of HW, aligning moment, and so on, are not considered in this torque map.

Seok-Hwan Jang [14] and et. al., in 2003, proposed a feedback force calculation scheme based on reference model of HW with lateral force measured from a torque sensor. For this, there is no need of the second torque sensor at RW while the force feedback is governed only by reference model of HW and the measured aligning torque.

C. Torque sensor-based method

Researchers from the field of robotics have proposed torque-sensor based solution in which a steer-by-wire system is treated as a teleoperation system with position-force control architecture [6], [9], Sanket Amberkar and et. al. worked on A control system methodology of steer-by-wire systems based on position-force control scheme (Fig. 5).

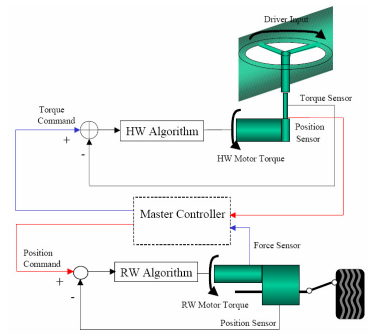


Fig. 5 Position-force control scheme

IV. DIRECT CURRENT MEASUREMENT METHOD

A. Overview of direct current measurement method

In our proposed method, there are two control loops Fig. 6. In first loop, HW encoder detects HW movements and sends HW angle as an input to a PID position controller. Then, the controller gives control signal as current signal to RW actuator. The position synchronization of the HW and RW is ensured by be the PID controller. RW angle θ_{rw} plays a role as feedback signal.

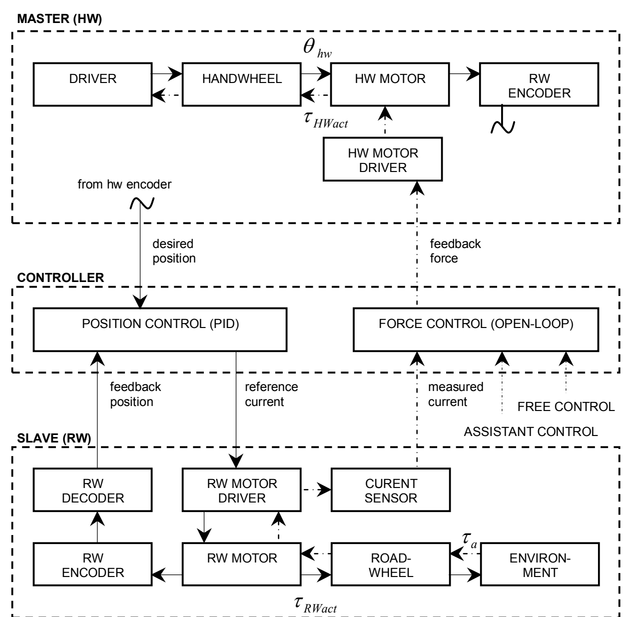


Fig. 6 Overview of steer-by-wire structure

When the RW DC motor actuates the roadwheels accordingly, a proportional current signal inside the motor driver of occurs at the same time. Fortunately, the value of the current signal depends on the load applied on motor shaft because of the current-torque relationship of DC motors.

A current sensor unit is connected to RW's motor driver and RW's motor in series for measuring current signals. This signal is later used for creating force feedback. To create realistic feedback, the vehicle speed and the HW angle are employed to produce the assistance force. To make HW stable and easy to be controlled, a free control algorithm is developed based on the HW angle. The next section will comprehensively describe the force feedback implementation and free control.

B. Reproducing driving feeling

As discussed in section III, force feedback contains moments of inertia, damping, and Coulomb friction and aligning force. The force feedback of HW is proposed in equation (5). Where i is RW actuator current. This current tells the RW part's properties which are various depending on steering system mechanism, road condition, side-slip angle, and so on. T_{fc} is a free control torque discussed in section V.C in this paper.

$$\tau_{feedback} = G_{feel}(K_t.i - \tau_{assist}) + T_{fc} \quad (5)$$

Basically, in automotive power steering, the assistant torque is used to reduce the force feedback at the lower speed (the speed of the vehicle) or tighter at the higher speed [6]. Therefore, assistant toque τ_{assist} is introduced in equation (6).

$$\tau_{assist} = K_a \theta_{hw}{}^2 - sign(\dot{\theta}_{hw}) K_v V_v \quad (6)$$

From equation (5) and (6), the total force feedback is reproduced. In particular, this feedback torque is tuned through three steps. First, pure force is calculated from the measured current signal. This torque is quite hard like steering system without any assistant means. Therefore, assistant torque based on the equation (6) is done in the second step. We may turn HW angle gain K_a , and velocity gain K_v to obtain the desired force magnitude. In the third step, there is a need to tune two gains (G_{feel} , and K_{fc}) at the same time to achieve a desired force feedback profile. A gain set selected in this research is provided in the table of simulation parameters [Table 1].

C. Free control

Traditionally, free control response has been solved by adding damping (in the case of EPS) or friction to the system [6] (in the case of hydraulic steering). In previous research, a free control algorithm for EPS application is done by Bolourchi and Etienne [12]. Sanket Amberkar, et al mentioned that for the free control of a steering systems as well as SBW systems, a quick return of HW to center with minimal overshoot is desired [6]. However, their research did not mention how a good free control is implemented. Our proposed idea is to add additional damping to SBW system. Thus, we now introduce a new torque to the system called free control torque. This torque is a product of a free control gain K_{fc} , and HW angle, written in equation (7).

$$T_{fc} = -K_{fc} * \theta_{hw} \quad (7)$$

By introducing this force to the system, the force feedback will change. Fortunately, because the special design of non-physical connection of by-wire technology allows us to easily adjust the force feedback by changing the HW angle gain and velocity gains or the scaling factor of RW motor's torque in equation (5).

V. SIMULATION

A. Overview of simulation

PID controller for position control of steering system aims to have a good position tracking of RW and HW. An open loop control for force feedback based on the measured current signal is conducted as algorithms described in section 4. Free control quality is evaluated by the returning force verse HW angle, [15]. Simulation parameters are chosen as follows.

TABLE 1. SIMULATION PARAMETERS

J_w : 0.019 (kg.m^2/s^2)	The inertia and damping constant of steering system. These constants are chosen based on steering system identification done by [13].
b_w : 0.368 (Nms)	
G_{feel} : 1	This gain is selected based on comfortable feelings of drivers
K_t : 0.581 (Nm/Amp)	From the motor datasheet
K_a : 0.3	Assistance gain is chosen based on amount of desired torque and feedback torque profiles
K_v : 3	Assistance gain is chosen based on the amount of desired torque and feedback torque profiles
V_v : 60 (km/h)	A certain velocity selected for simulating in this paper
K_{fc} : 0.02	This is selected based on the behaviors of free control. In the best case, this gain ensures lowest oscillations of HW in free control.
K_p :5.5, K_d : 0.08	These are gains of PD controller. Turning method: Ziegler–Nichols

B. Simulation result

Position tracking, A good position tracking also can be achieved in this method shown in Fig. 7. The simulation parameters are: K_p =5.5; K_d =0.08; Step size: 0.001 (s).

The result shows that error of the system is significantly reduced. In this method, the error is about 0.06 rad) while it is normally about 0.1 - 0.59 rad mentioned in [10], [15]. The result of postion tracking in J-command is shown in free control of HW (Fig. 15). The J-commend is defined as a quick change in HW input. This command is given by the driver when an obstacle is suddenly found.

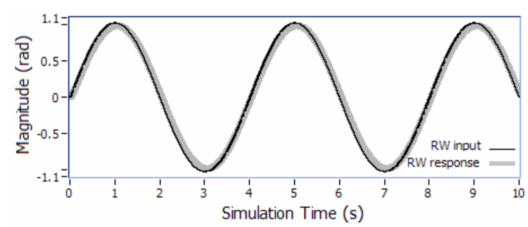


Fig. 7. Position tracking of SBW

Realistic haptic feedback, the force feedback is first recreated based on current signal without any amount of assistant force and free control force. In addition, without tire-to-ground contact, the relationship of HW angle as force feedback is a rectangular profile shown in Fig. 8.

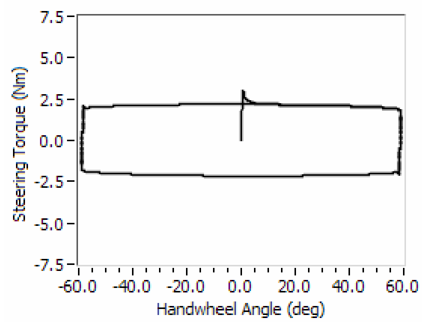


Fig. 8. HW position vs. Force feedback without tire-to-ground contact

In normal working condition, the tires travel on road surface and aligning torques at two front wheels happen. When the steering angle increases, the aligning torque become larger because of the increment of the pneumatic trail shown in Fig. 9.

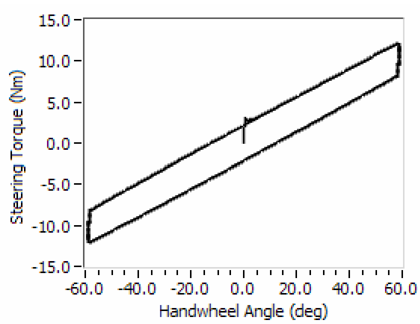


Fig. 9. HW position vs. Force feedback with tire-to-ground contact

The final force feedback is achieved after introduction of assistant torque based on HW angle and vehicle velocity, Fig. 10.

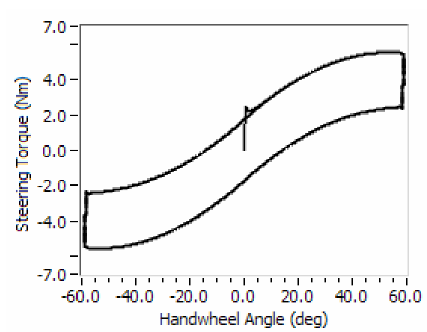


Fig. 10. HW position vs. Force feedback with assistant torque

Fig. 11 is the comparison of simulation of torque map method and the proposed method. The simulation result clearly shows that, the proposed method can achieve the realistic haptic feedback which provides the realistic driving feelings.

In our proposed method, the steering dynamics is included to implemented force feedback. These dynamic effects are represented in term of current signal. Therefore, the obtained force feedback not only depends on HW angle and vehicle velocity, but also relates to road condition, tire properties, yaw movement of vehicle and so on. This is most the benefit contributions which are not solved in torque map-based approach.

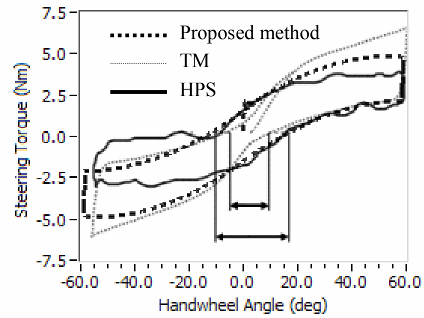


Fig. 11. Comparison of proposed method and others
HPS: hydraulic power steering, TM: torque-map method

In addition, with the direct current measurement method, the force feedback can be abstained and easily adjusted Fig. 12. In this result we have three torque profiles equivalent to the free control gains are 0.01, 0.02, and 0.03. For the result of total force feedback shown in Fig. 11, the free control gain is chosen as 0.02.

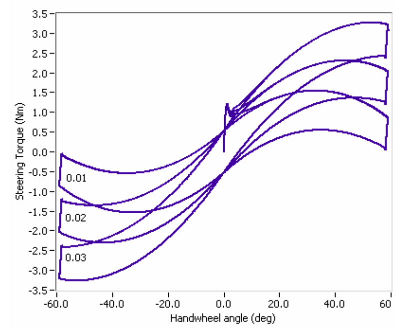


Fig. 12. Different force feedback magnitude with varying free control gain

The rotating frequency of HW is changed from 0.05 to 2Hz in different experiments. The results in Fig. 13 show that steering torque is significantly affected by HW frequency. This is an important finding because this effect is ignored in torque-map based method.

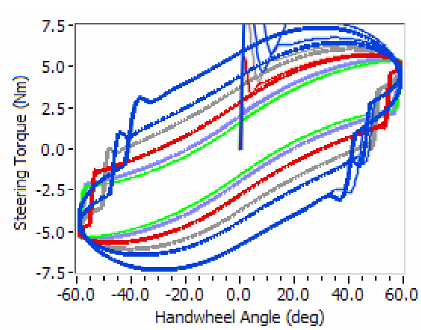


Fig. 13. Different force feedback magnitude with varying free control gain

Free control, the simulation result in Fig. 13 and Fig. 14 has proved that, the free control torque has significantly reduced the oscillation of HW. This could be explained easily because when the free control factor is added to the system, the hysteresis of steering system is reduced shown in Fig. 11. The hysteresis of proposed method is reduced to -5 to 5 degrees while it was from -10 to 10 degrees in torque map method.

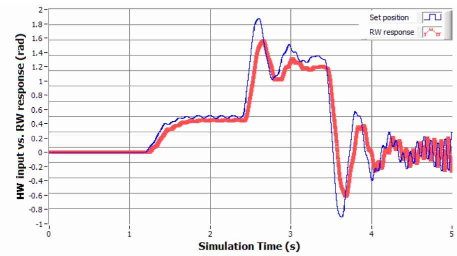


Fig. 14. HW behavior without free control torque (T_{fc})

(Without scaling of HW angle and WR angle)

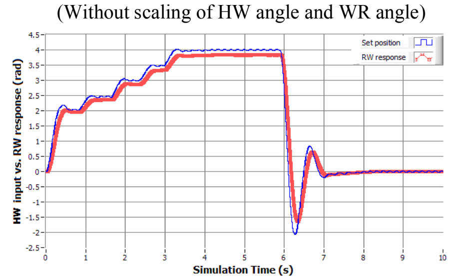


Fig. 15. HW behavior with free control torque (T_{fc})

(Without scaling of HW angle and RW angle)

VI. CONCLUSION AND FUTURE WORK

This research have proposed a novel control scheme for steer-by-wire development in which the current sensor could be used to fully measured steering torque. Since, current sensors are cheap and available in typical industrial and automotive applications. This solution offers a cheaper and simper method to reproduce the driving feeling. The force feedback control algorithm is developed not only to give the realistic driving feelings, but also improve the returnability and free control performance while remain the fundamental requirements of conventional steering systems such as position tracking.

We suggest that, for steer-by-wire systems, a study of force feedback of very light handwheel in novel design of human/vehicle interfaces. In this case, handwheel's mass should be included in force calculation scheme to recreate driving feelings which is the same as conventional power steering systems. In addition, the study of different force feedback of different handwheel types might be benefit for steering control of vehicles. The lock-to-lock properties of steer-by-wire happened at the largest steering angle will be implemented in the near future.

ACKNOWLEDGEMENT

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